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A New Experimental Approach to Evaluate Plasma-induced Damage in Microcantilever

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Abstract

Plasma etching, during micro-fabrication processing is indispensable for fabricating MEMS structures. During the plasma processes, two major matters, charged ions and vacuum–ultraviolet (VUV) irradiation damage, take charge of reliability degradation. The charged ions induce unwanted sidewall etching, generally called as "notching", which causes degradation in brittle strength. Furthermore, the VUV irradiation gives rise to crystal defects on the etching surface. To overcome the problem, neutral beam etching (NBE), which use neutral particles without the VUV irradiation, has been developed. In order to evaluate the effect of the NBE quantitatively, we measured the resonance property of a micro-cantilever before and after NBE treatment. The thickness of damage layer (δ) times the imaginary part of the complex Young's modulus (E_{ds}) were then compared, which is a parameter of surface damage. Although plasma processes make the initial surface of cantilevers damaged during their fabrication, the removal of that damage by NBE was confirmed as the reduction in δE_{ds}. NBE will realize a damage-free surface for microstructures.

Abstrak

Pendekatan Eksperimental Baru untuk Mengevaluasi Kerusakan yang Disebabkan oleh Plasma pada Kantilever Mikro. Pengetsaan plasma selama proses fabrikasi-mikro adalah peristiwa yang tak terhindarkan dalam proses fabrikasi struktur-struktur MEMS. Selama proses plasma berjalan, dua materi utama, yaitu ion bermuatan dan kerusakan iradiasi vakum-ulraviolet (VUV), berperan penting dalam memastikan reliabilitas proses degradasi. Ion-ion bermuatan menyebabkan pengetsaan sisi-dinding yang tidak diharapkan, suatu peristiwa yang umumnya disebut "penotsaan" ("*notching*"), yang menyebabkan degradasi berkekuatan rapuh. Selanjutnya, iradiasi VUV menimbulkan kecacatan kristal pada permukaan etsa. Untuk mencegah hal ini, pengetsaan sinar netral (*neutral beam etching* atau NBE), yang menggunakan partikel-partikel netral tanpa iradiasi VUV, telah dikembangkan. Untuk dapat mengevaluasi efek dari proses NBE secara kuantitatif, kami mengukur properti resonansi dari kantilever mikro sebelum dan setelah proses NBE. Ketebalan lapisan rusak (δ) yang dikalikan dengan bagian imajiner dari modulus Young kompleks (E_{ds}) kemudian dibandingkan; hasilnya menjadi parameter kerusakan permukaan. Meskipun proses plasma menyebabkan permukaan awal kantilever mengalami kerusakan selama proses fabrikasi, perbaikan kerusakan itu oleh proses NBE telah terbukti karena reduksi δE_{ds}. NBE dapat menghasilkan permukaan yang bebas-rusak pada struktur-struktur mikro.

Keywords: cantilever, neutral beam etching, surface loss

1. Introduction

Plasma etching, during micro-fabrication processing, is indispensable for fabricating MEMS structures. However, the plasma processes have two major matters; charged ions damage and vacuum ultraviolet (VUV) irradiation damage. The charged ions induced unwanted sidewall etching, generally called as "notching", which conduct a degradation of brittle strength [1]. Furthermore, the VUV irradiation gives rise to crystal defects on the etching surface, and thus degrade mechanical/electrical stability [2]. To overcome the problem, neutral beam etching (NBE), which use neutral particles without the VUV irradiation, has been developed [3]. The NBE is expected to provide damage-free etching and will be profitable for micro electro mechanical devices.

In this paper, to examine the damage free effect of the NBE quantitatively, the Q-value change of a thin cantilever is measured. This cantilever, made of silicon, is initially introduced plasma damage during its fabrication process, but the removal of the damage by NBE was explicitly observed by recovery of the Q-value.

2. Experiment

The Q-value of a cantilever is determined by damping factors relating to cramping and surface condition, and surrounding atmosphere. Hence the total Q-value (Q_{Total}) can be expressed as following equation [4]:

$$Q_{Total}^{-1} = Q_{Support}^{-1} + Q_{TED}^{-1} + Q_{Surface}^{-1} \tag{1}$$

where, $Q_{Support}$, Q_{TED} and $Q_{Surface}$ denote the part of quality factors due to support loss, thermo elastic damping and surface loss, respectively. In this study, we ignore any other losses mentioned above. The air-damping factor deserves our attention, but it can be negligible in the vacuum condition (<10^1 Pa) [4]. In general, for submicron-thick cantilevers operating at order of kHz frequency, Q_{TED} is also negligible [4]. $Q_{Support}$ was studied theoretically using a two-dimensional theory that modeled the support structure as an infinitely large elastic body [5]. This calculation was result in the estimation of $Q_{Support} \fallingdotseq 2.17\ l^3/h^3$, where l and h are length and thickness of a cantilever. For the all of the cantilevers were described here, l/t >39 giving $Q_{Support} > 1.3 \times 10^5$.

The effect of plasma-induced damage appears $Q_{Surface}$; hence, our purpose in this study is to measure $Q_{Surface}$ of the cantilever. In order to understand the $Q_{Surface}$, in detail, we now consider the complex-value of Young's modulus $E=E_{Si}+iE_{dSi}$, where E_{Si} is the conventional (real-value) Young's modulus and E_{dSi} is the dissipative part, which is usually small compared to E_{Si}. For dissipative processes that occur on the atomic scale (such as motion of lattice defects), E_{dSi} can be related to be a property of the material and its defects. While the E_{dSi} represents the loss of the cantilever body, we characterize the surface layer by complex modulus $E_{Surface}=E_S+iE_{dS}$ and damage layer thickness δ (Fig. 1). From a cantilever of Q-value definition as $Q=2\pi W_0/\Delta W$, where Wo is the stored vibrational energy and ΔW is the total energy loss per cycle of vibrational energy and ΔW is the total energy lost per cycle of vibration, we can obtain $Q_{surface}$ under condition of simple rectangle cantilever model as a following equation [5-6]:

$$Q_{Surface} = \frac{E_{Si}}{\delta E_{ds}} \frac{h}{6} \tag{2}$$

where h is thickness of the cantilever. In this equation, we easily understand that $Q_{Surface}$ is reciprocal function of δE_{ds}, that is, the larger the E_{ds} is, the smaller the $Q_{Surface}$ is. And since E_{Si} and h are determined the design and the material constant, $Q_{Surface}$ is the only function of E_{ds}.

Figure 2 shows the plot of total Q_{Total}, it was found that the Q_{Total} for a thickness less than 4 µm (l/t =37.5) is dependent on the δE_{ds} value and linear function for the cantilever thickness especially less than 2 µm (l/t =75) region. In this condition, Q_{Total} that is almost linear with the thickness and the slope is dependent on δE_{ds}; Q_{Total} dominated by $Q_{surface}$ compared with other losses. In this paper, we employ the δE_{ds} to discuss the surface loss quantitatively.

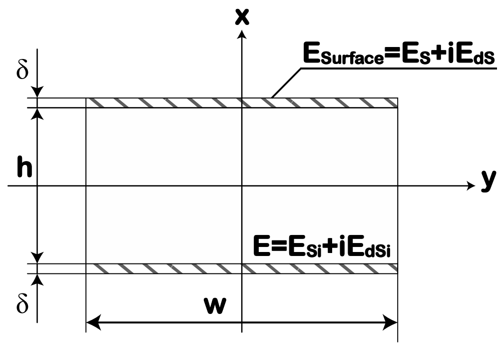

Fig. 1. Cross Section Model for Simple Rectangle Cantilever with Surface Damage, Young's Modulus of Material is Modeled by Consisting Complex-valued

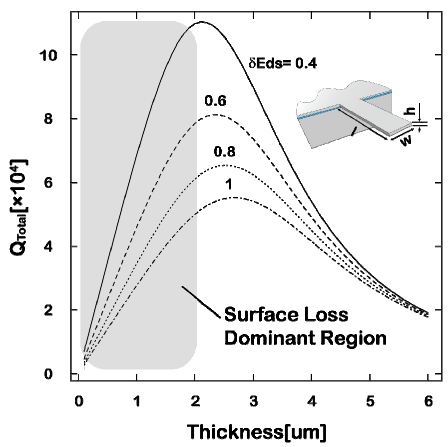

Fig. 2. The Theoretical Curve of Q_{Total} as a Function of its Thickness. The Length and Width are 150µm and 30 µm with the Cantilever, Respectively. *δEds* is a Parameter Related to Surface Energy Loss

3. Results and Discussion

We employ the special designed cantilever to evaluate plasma-induced damage, and fabricated using surface micro machining technique. Upon fabrication of this cantilever, a SiO_2 mask was formed by plasma CVD and surface damage has been introduced simultaneously during its deposition, and the SiO2 mask was removed by vapor HF prior to the measurement. Designed dimension of the cantilever are 150 µm long, 30 µm wide and 1.5 µm high, respectively.

Figure 3 shows a schematic image of the measurement system for the cantilever. The cantilever was mounted in a vacuum test chamber ($<3.0\times10^{-3}$ Pa). And the cantilever was driven by the small-pulsed signal of an excitation laser, which brought the base of a cantilever into focus and caused periodic bending moment due to thermal excitation. The laser Doppler velocimeter was employed to measure the vibration velocity at the tip of the cantilever and measured value was sent to the network analyzer. In this manner, the network analyzer displayed the peak of resonance frequency and we were able to obtain the Q-value of the cantilever.

The NBE with slow etching rate that was 50 nm/min etched the cantilever surface, having the plasma-induced damage. First, the NBE etched surface of the cantilever for 1 min and then Q-value and resonance frequency were measured. This set of the NBE and the measurement procedures were then repeated three times but the NBE times were 1min, 10 min and 5 min, respectively.

Figure 4 plots the measured Q-value, on the average, with 1σ error bars as a function of a thickness of the cantilever, which was calculated from the resonance frequency (f_n) using the following relation:

$$f_n = \frac{k_n^2 h}{2\pi l^2}\sqrt{\frac{E_{Si}}{12\rho_{Si}}} \tag{3}$$

where, k_n is the constant of the n th mode resonance (k_1 = 1.875), l and ρ_{si} are length and density of the cantilever. The theoretical Q_{Total} of the cantilever is also shown in figure 4 with several δE_{ds} values as a parameter. The initial measured Q-value was relatively low owing to the surface damage, which was introduced by plasma CVD during the fabrication process. As the surface was slightly etched, Q value increased dramatically and then gradually decreased along with the theoretical line of δE_{ds} = 0.5.

In this result, we indicate validity of the evaluation method using the cantilever, and effect of NBE to decrease the plasma-induced damage.

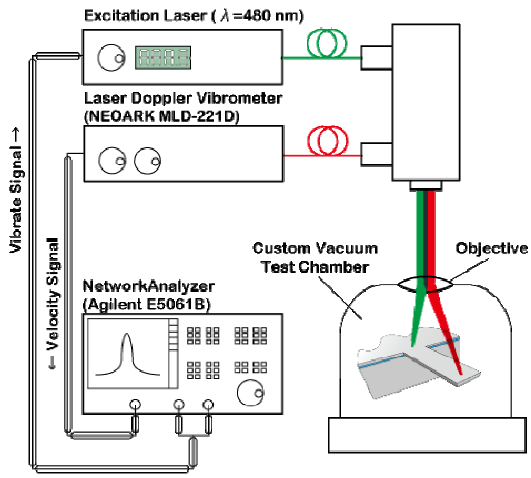

Fig. 3. The Measurement System of the Cantilever

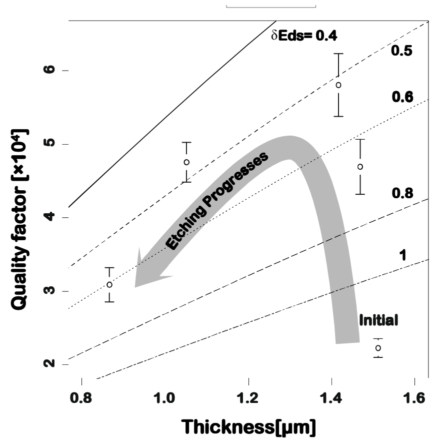

Fig. 4. The Experimental Result of Average Quality Values as a Function of the Cantilever Thickness that is Treated by NBE, and Several Values of Theoretical Curve of Q_{Total} are also Shown

4. Conclusions

We here propose a new experimental method to evaluate plasma-induced damage in a micro-cantilever. From the theoretical consideration, a cantilever size is established the $Q_{Surface}$ dominant region. That is, the dimensions have 150 µm long, 30 µm wide and 1.5 µm high, respectively. This cantilever, made of silicon, is introduced plasma damage during its fabrication process, and observed the progress of Q-value at intervals of few minutes NBE. As a result, the initial measured Q value was large due to the damage existed on the fabricated surfaces, but after slightly etched by NBE, Q-value increased dramatically dropped drastically and then gradually decreased along with the theoretical line of δE_{ds} = 0.5.

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